ASM Sc. J., 19, 2024

https://doi.org/10.32802/asmscj.2023.1476

Mechanical Response and Failure Analysis of Stainless-Steel Beams Exposed to Elevated Temperatures

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This research investigates the structural behaviour of stainless-steel beams (SSBs) when subjected to extreme temperatures, specifically in the context of fire-induced deformations. High temperatures, typical of fire occurrences, exert large thermal loads on SSBs, leading in material property changes that make the metal more brittle, stiffer, and brittle. The objective of this study is to investigate extensively the behaviour of SSBs under the combined impact of heat transfer and applied loads, with a focus on substantial deflections. To completely assess the performance of SSBs, we undertake parametric investigations and systematic research efforts. The initial phase comprises a thorough review of relevant data about the behaviour of SSBs at increased temperatures. Afterwards, a parametric study of the web section is conducted to determine the performance of the SSBs under exposure to fire and applied stresses. In order to ease the numerical research, the finite element (FE) program ABAQUS CAE is used to simulate stainless steel I-section beams of varying diameters subjected to realistic fire conditions according to the ISO 834 standard fire curve. The average discrepancy between numerical forecasts and experimental data for six separate models about the final temperature readings is 2.74 percent. Prior to actual collapse, the axial displacement of the SSBs decreases by around 7.5%, showing significant temperature influences on their strength. In addition, the axial deformation of the SSBs exhibits greater displacements in the web portion than in the flange section following fire exposure and loading. This discovery highlights the need to take into account the unique thermal expansion and stiffness characteristics of the web and flange components during fire occurrences. Utilising the finite element approach in ABAQUS reveals the resistance of SSBs to increased temperatures. The findings highlight the potential advantages of using stronger SSBs to maximise the structural response under fire conditions. This study gives useful insights into the thermal behaviour of SSBs and has important implications for building fire-resistant structures, boosting the fire safety of constructions, and enhancing their resistance against fire risks.

Keywords: Stainless-steel beam (SSB); elevated temperature; fire; finite element method (FEM); deformation; heat transfer analysis

I. INTRODUCTION

Stainless steel has emerged as a high-performance structural material of choice in the rest of the world, including civil engineering infrastructure projects, in recent years (Ding *et al.*, 2023; Du *et al.*, 2023; Gardner *et al.*, 2016; Hao *et al.*, 2023; Huang *et al.*, 2023; Khan & Latheef, 2023). Its use in bridge structures has gotten a lot of attention, owing to its corrosion resistance and higher tensile strength than

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conventional concrete reinforcements. Because of this advantageous combination of properties, concrete thickness can be reduced, resulting in lighter and more manageable construction processes on-site. While stainless steel has many advantages in terms of durability, maintenance, and low life-cycle costs, its susceptibility to thermal degradation when exposed to fire is still a major concern (Ding *et al.*, 2023; Du *et al.*, 2023; Fan *et al.*, 2017; Khan & Latheef, 2023; Li *et al.*, 2022; Suo *et al.*, 2021; Tao *et al.*, 2019; Yan *et al.*, 2022). Rapid heat transfer in metal structures during fires causes a loss of material strength and stiffness, potentially jeopardising structural integrity and increasing the risk of collapse. Despite these obstacles, the construction industry continues to recognise and capitalise on the potential of stainless steel, particularly considering the increasing demand for buildings with enhanced functionality and aesthetic appeal, as well as the growing need to address corrosion-related issues in conventional steel structures (Chen & Young, 2006; Fan *et al.*, 2020; Suo *et al.*, 2021; Yan *et al.*, 2022). Previous research efforts focused primarily on individual stainless-steel components, such as statically determinate columns and beams, leading to the formulation of component-based fire design recommendations, such as the EN 1993-1-2 guidelines (Gardner, 2007; Gardner & Baddoo, 2006; Gardner & Ng, 2006; Kucukler *et al.*, 2020, 2021; Ng & Gardner, 2007; Pournaghshband *et al.*, 2019, 2019). However, research into the structural behaviour of stainless-steel beams (SSBs) at elevated temperatures has received little attention. This research seeks to fill that gap by shedding light on the thermo-mechanical response of SSBs when exposed to fire, with a particular emphasis on their behaviour and performance under such extreme conditions. This study aims to contribute valuable insights to the fields of fire engineering and construction by demonstrating the feasibility of restoring fire-affected stainless-steel elements with minimal downtime and low additional costs. The findings of this study have the potential to significantly inform the development of innovative fire-resistant design strategies, thereby improving the resilience and safety of stainless-steel structures in fire-prone environments. Furthermore, the study's findings have practical implications for speeding up the repair and restoration of fire-damaged stainless-steel elements, allowing for more efficient and reliable steel-based construction practises throughout Malaysia's construction industry.

A thorough understanding of material properties and their response to high temperatures is critical in structural fire design. The behaviour of materials at elevated temperatures, which includes critical aspects such as stress-strain properties, thermal expansion, thermal conductivity, specific heat, and unit mass, has a significant impact on their performance during fire exposure (Gardner, 2007; Gardner & Ng, 2006; Khorasani *et al.*, 2015; Kodur & Khaliq, 2011; Maraveas *et al.*, 2013; Mirza & Uy, 2009). The ability of a material to retain strength and stiffness at high temperatures is critical in the development of fire-resistant structures that can withstand the thermal stresses and deformations caused by fire incidents. When compared to conventional carbon steel, stainless steel exhibits superior behaviour at elevated temperatures due to its unique composition and alloying elements (Gardner & Ng, 2006). Because of the significant impact of alloying elements, stainless steel retains its mechanical properties more effectively at higher temperatures, making it an appealing option for fire-resistance applications. Because of this distinct advantage, stainless steel is a promising candidate in the search for robust and resilient structural elements that can withstand the harsh conditions of fire exposure. Incorporating insights derived from material responses to high temperatures is critical in rational fire engineering design and implementation. Engineers can create fire-resistant structural solutions that improve safety and durability in fire-prone environments by leveraging the inherent benefits of stainless steel. As the demand for fire-resistant building materials grows, stainless steel emerges as a compelling option, demonstrating its ability to maintain structural integrity even under extreme thermal conditions. As a result, the prudent use of stainless steel in fire-resistant designs can significantly contribute to advancing fire engineering practises and ensuring the longevity and safety of modern construction projects.

The existing body of research emphasises the diverse capabilities of various types of stainless steel in strengthening beams. Prior research (Gardner, 2005; Gardner & Ng, 2006; Pournaghshband *et al.*, 2019) has revealed that, when compared to carbon steel beams, austenitic SSBs have the advantage of being able to withstand elevated temperatures before succumbing to catenary action. Surprisingly, despite the higher thermal expansion of austenitic stainless steel, these beams have comparable maximum tensile catenary forces to carbon steel counterparts. Despite the insightful findings on austenitic stainless steel, there is a significant research gap regarding the effects of varying web sections and the application of fire loading on standard SSBs. The scarcity of studies on the fire resistance stress and strength of these configurations necessitates careful investigation. To fill this knowledge gap, our current research aims to investigate the intricate interplay between temperature, applied load, and various dimension sizes in order to determine their collective influence on the fire resistance and stress-strain relationship of SSBs. Using a rigorous and systematic approach, we hope to establish a relationship between temperature and applied loading, thereby improving the fire resistance and load-bearing capacity of SSBs. The use of the finite element method as a powerful analytical tool allows for a thorough evaluation of the structural behaviour of SSBs at elevated temperatures, allowing for a more in-depth understanding of their thermo-mechanical response. The expected outcomes of this scholarly endeavour will make significant contributions to the advancement of fire engineering practices. Our research aims to provide critical design considerations for optimising the fire performance of stainless-steel structures by uncovering the intricate factors that shape the structural behaviour of SSBs under fire conditions. These findings, in turn, are expected to strengthen the safety and resilience of stainless-steel beams in fire-prone environments, ushering in a new era of innovative fire-resistant design strategies for improved structural performance. Finally, the findings of this study have the potential to inform and elevate future design practices, instilling greater confidence in the prudent use of stainless steel in fire-resistant construction. By incorporating the findings of our research, the construction industry can chart a course toward safer and more robust building solutions, effectively mitigating the risks of fire incidents and upholding the principles of structural integrity and occupant safety.

II. RESEARCH METHODOLOGY

This section provides a thorough explanation of the critical components involved in the study of stainless-steel beams (SSBs) under the influence of elevated temperature conditions. It entails a thorough examination of material and thermal properties, the creation of a reliable numerical model, parametric studies to assess the impact of varying parameters, considerations of heat transfer mechanisms, and the expert application of finite element modelling techniques.

A. Material and Thermal Properties of SSB

This section provides a thorough explanation of the critical components involved in the study of stainless-steel beams (SSBs) under the influence of elevated temperature conditions. Austenitic stainless steels, ferritic stainless steels, martensitic stainless steels, duplex stainless steels, and precipitation hardening steels are the five types of stainless steels based on their chemical composition and thermomechanical treatment. Each group has various qualities, including strength, corrosion resistance, and ease of production. The element of stainless steel must include at least 10.5% chromium (Cr) to provide corrosion resistance. Also present as alloying elements are carbon (C), nickel (Ni), manganese (Mn), molybdenum (Mo), copper (Cu), silicon (Si), sulphur (S), phosphorus (P), and nitrogen (N) (Gardner, 2005). Table 1 presented the chemical composition for three grades of stainless steel (Gardner, 2005). First, grade 1.4301 austenitic stainless steel I-section beam testing revealed that its stainless-steel surface has been coated, resulting in a beautiful, long-lasting coating. Second, because it resists corrosion, it is one of the most long-lasting construction materials. In accordance with EN ISO 13919-1, all the tested I-section members were made by laser welding hot-rolled grade 1.4301 austenitic stainless-steel plates (Xing *et al.*, 2021). In line with the manufacturer's mill certifications, Tables 2 and 3 detail the chemical composition and material qualities of the tested I-section members. where f_y, the mill, is the 0.2 per cent proof stress, $f_{p1.0}$, the mill is the 1 per cent proof stress, and f_u, the mill, is the ultimate tensile stress (Xing *et al.*, 2021).

Table 1. Chemical compositions for three grades of stainless steel (Gardner, 2005)

Chemical composition (% by mass)			
Element	**Steel Designation (Number)**		
	1.4301 (304)	**1.4401 (316)**	**1.4462 (2205)**
Carbon (C)	≤ 0.07	≤ 0.07	≤ 0.030
Chromium (Cr)	17.00 to 19.50	16.50 to 18.50	21.00 to 23.00
Nickel (Ni)	8.00 to 10.50	10.00 to 13.00	4.50 to 6.50
Molybdenum (Mo)	-	2.00 to 2.50	2.50 to 3.50
Manganese (Mn)	≤ 2.00	≤ 2.00	≤ 2.00
Silicon (Si)	≤ 1.00	≤ 1.00	≤ 1.00
Phosphorus (P)	≤ 0.045	≤ 0.045	≤ 0.035
Sulphur (S)	≤ 0.015	≤ 0.015	≤ 0.015
Nitrogen (N)	≤ 0.11	≤ 0.11	0.10 to 0.22
Titanium (Ti)	5×C to 0.70	5×C to 0.70	-
Tungsten (W)	-	-	0.50 to 1.00

Table 2. Chemical Compositions of Stainless-Steel Grades EN 1.4301 (Xing *et al.*, 2021)

Specimen	**I-198×99×4.5×7**
C (%)	0.026 0.024
Si (%)	0.41 0.40
Mn (%)	1.37 1.38
P (%)	0.032 0.031
S (%)	0.001 0.002
Ni (%)	8.00 8.05

Table 3. Material Properties in Mill Certificates (Xing *et al.*, 2021)

Specimen	**I-198×99×4.5×7**
$f_{y,mill}$ (N/mm^2)	312 313
$f_{p,1.0,\ mill}$ (N/mm^2)	349 348
$f_{u,mill}$ (N/mm^2)	630 625
$\varepsilon_{f,mill}$ (%)	51 52

The SSBs were subjected to a prescribed standard temperature for fire exposure as similar to carbon steel in accordance with the ISO834 standard fire curve (ISO, 1999) as shown in Figure 1, as stipulated by BS EN 1991-1-2 (BSI, 2002) and BS EN 1993-1-2 (BSI, 2005a), allowing a rigorous evaluation of their performance under realistic fire conditions. A thorough characterisation of material properties is critical for facilitating rigorous numerical modelling of SSBs. As a result, the SSB model carefully considered six fundamental material attributes: density, elasticity, plasticity, thermal conductivity, thermal expansion, and specific heat. These properties have intrinsic importance in governing the structural behaviour of SSBs in high-temperature scenarios. Basically, material properties for stainless steel beam at elevated temperature were extracted similar with the carbon steel properties as prescribed in Eurocode 3: Design of steel structures - Part 1-2: General rules - Structural fire design (BS EN 1993-1-2 (2005)) (BSI, 2005a). For all the density, elastic, plasticity, thermal conductivity, thermal expansion and specific heat properties were obtained from Eurocode (BSI, 2002; 2005a) and previous research work (Zakwan *et al.*, 2015; 2018; Zakwan *et al.*, 2019; Zakwan *et al.*, 2019). The variation of the thermal conductivity, specific heat and thermal expansion at elevated temperature were illustrated in Figure 2, 3 and 4 respectively.

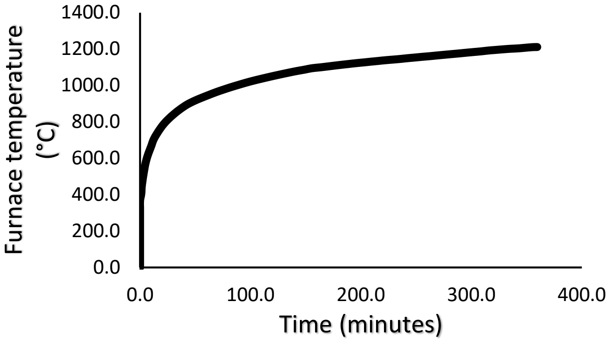

Figure 1. Standard Fire Curve ISO834 (BSI, 2002)

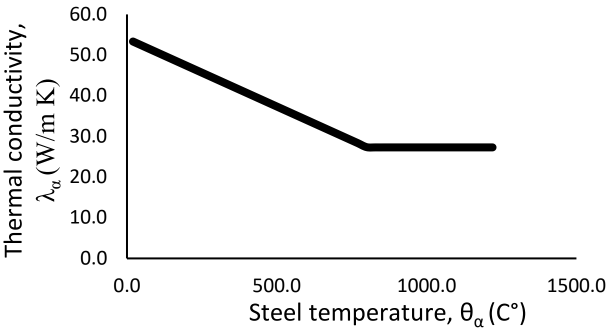

Figure 2. Thermal conductivity of carbon steel at elevated temperature (BSI, 2005a; 2005b)

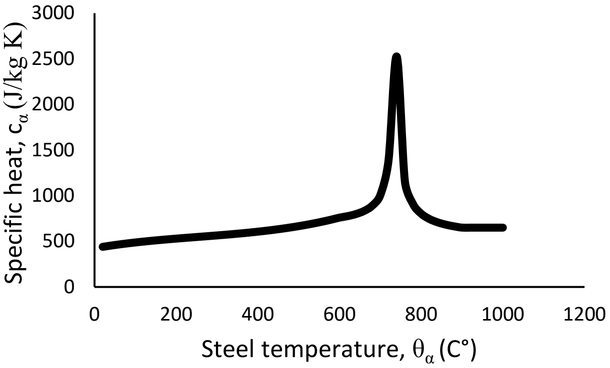

Figure 3. Specific heat of carbon steel at elevated temperature (BSI, 2005a; 2005b)

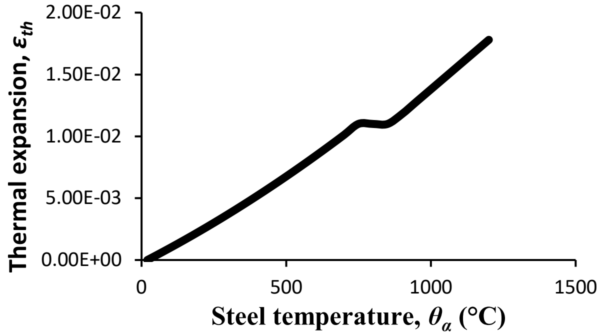

Figure 4. Thermal conductivity of carbon steel at elevated temperature (BSI, 2005a; 2005b).

It is well-known that a fire's temperature changes and rises with time. In reaction to heat transmission, the SSB must interact with the heat on its surface. In this structure, the fire was spread to the bottom and sides of the beam, while the top is covered by an aerated concrete slab block. As indicated in Figure 1, the model's amplitude is based on a tabular amplitude from the ISO834 Standard Fire Curve (BS EN 1991-1-2). The primary components of a heat transfer study are convection and radiation across the fire's border and conduction within the structural parts. In general, when exposed to fire, every structural part suffers heat transfer produced by convection and radiation processes. After the early phase of a fire, the radiation is far more dominant than the convection. The thermal actions on the surface of the structural elements can be represented with net heat flux, $\dot{h}_{net}$. A net heat flux, $\dot{h}_{net}$ is imposed on the bare surface of structural elements as follows:

$$\dot{h}_{net} = \dot{h}_{net,c} + \dot{h}_{net,r} \qquad (W/m^2) \qquad (1)$$

The net convective heat flux, $\dot{h}_{net,c}$ can be calculated as follows:

$$\boldsymbol{\dot{h}_{net,c} = \alpha_c \cdot (\Theta_g - \Theta_m) \qquad (W/m^2)} \qquad (2)$$

where, α_c= the coefficient of heat transfer by convection (W/m^2K) , Θ_g = the gas temperature near the fire exposed member (°C) and Θ_m = the surface temperature of the member (°C). The value of the coefficient of heat transfer by convection, α_c can be retrieved from Table 4 as follows:

Table 4. The coefficient of heat transfer by convection as in BS EN 1991-1-2 (BSI, 2002)

Fire model or exposed condition	α_c (W/m^2K)
Standard fires	25
External fires	25
Hydrocarbon fires	50
Parametric fires	35
Unexposed side of separating members without radiation	4
Unexposed side of separating members with radiation	25

The net radiative heat flux, $\dot{h}_{net,r}$ is approximately obtained from BS EN 1991-1-2 (BSI, 2002) as follows:

$$\dot{h}_{net,r} = \Phi \cdot \varepsilon_m \cdot \varepsilon_f \cdot \sigma \cdot [(\Theta_r + 273)^4 - (\Theta_m + 273)^4] \quad (W/m^2) \tag{3}$$

where, Φ = the configuration factor, ε_m = the surface emissivity of the member, ε_f= the emissivity of the fire, σ= the Stephan Boltzmann constant ($= 5.67x10^{-8}$ W/m^2K^4), Θ_r = the effective radiation temperature of the fire environment (°C) and Θ_m= the surface temperature of the member (°C). Generally, the emissivity of the fire, ε_f and the configuration factor, Φ is taken as 1.0. The configuration factor, Φ are solely depends on two effects, namely position effect and shadow effect. The surface emissivity of the member, ε_m can be taken from Table 5 as follows:

Table 5. Emissivity of materials

Material	The surface emissivity of the member, ε_m
Carbon steel (BSI, 2005a)	0.7
Stainless steel (BSI, 2005a)	0.4
Concrete (BSI, 2005b)	0.7
Others (BSI, 2002)	0.8

During the preliminary phase of the investigation, an extensive testing regime on grade 1.4301 austenitic stainless steel I-section beams was carried out. This testing revealed the presence of a visually appealing and long-lasting surface coating on the stainless-steel surface, which contributes to the beam's visual appeal and long-term performance. The coating's increased corrosion resistance increases the material's durability, elevating stainless steel to one of the most resilient construction materials capable of withstanding harsh environmental conditions, including exposure to corrosive agents. The inherent corrosion resistance of grade 1.4301 austenitic stainless-steel highlights its suitability for extended service life in a variety of construction applications. The findings confirm the material's remarkable resilience, reaffirming its position as a promising choice for long-lasting construction materials, addressing the industry's need for long-lasting and sustainable building solutions. This research project addresses a critical aspect of fire engineering and structural design by elucidating the behaviour of SSBs under elevated temperature conditions. This investigation's comprehensive findings have enormous practical implications, shaping fire-resistant design strategies and ensuring the safety and reliability of stainless-steel structures in fire-prone environments. The findings of this academic endeavour significantly contribute to the advancement of fire engineering practices, propelling the wider adoption of stainless steel as a preferred construction material, characterised by enhanced structural performance and prolonged service life, as the construction industry increasingly seeks robust and resilient building solutions.

Furthermore, this study recognises the critical role of convective heat transfer coefficient and emissivity, which represent the absorptivity of structural members, as critical determinants in shaping temperature development within structural elements, a factor that has been thoroughly studied in previous research (Kucukler *et al.*, 2021). The tested I-section members are meticulously fabricated using laser welding techniques on hot-rolled grade 1.4301 austenitic stainless-steel plates, adhering to the stringent guidelines of EN ISO 13919-1, ensuring a high level of precision and quality in the manufacturing process. Furthermore, the study emphasises the critical importance of accounting for second-order effects caused by thermal expansion, which may result in larger axial and lateral deformations in the SSBs, resulting in elevated member forces and moments (Kucukler *et al.*, 2021). These critical findings highlight the importance of including thermal expansion effects in the numerical modelling of SSBs under fire exposure scenarios in order to accurately capture their structural response under high-temperature conditions. Two distinct loading eccentricity values of 10 mm and 30 mm are judiciously incorporated to comprehensively validate the robustness and accuracy of the numerical model, facilitating a meticulous evaluation of the finite element modelling of SSBs exposed to fire. This methodical approach allows for a thorough evaluation of the model's ability to capture the intricate thermo-mechanical responses of the SSBs under varying loading conditions and fire exposure. Actual experimental data are meticulously interpreted within the numerical simulation framework of the SSBs to further strengthen the numerical model's reliability. Using the advanced computational software ABAQUS, the numerical modelling accurately represents the thermo-mechanical behaviour of the SSBs under fire conditions. The study aims to achieve a comprehensive understanding of the behaviour of SSBs when subjected to elevated temperatures by meticulously incorporating these critical aspects into the research methodology, laying the groundwork for improved fire-resistant design strategies and enhancing the fire performance and safety of stainless-steel structures. The extensive analysis and validation performed within the numerical framework provide valuable insights for fire engineering practices, enhancing the design and construction of resilient and fire-resistant structures and contributing to the industry's quest for long-lasting and sustainable building solutions.

Table 5. Emissivity of materials

Material	**The surface emissivity of the member, ε_m**
Carbon steel (BSI, 2005a)	0.7
Stainless steel (BSI, 2005a)	0.4
Concrete (BSI, 2005b)	0.7
Others (BSI, 2002)	0.8

B. Finite Element Method (FEM) Modelling

The incorporation of Finite Element Analysis (FEA) has greatly aided in the prediction of failure in materials under uncertain stress conditions, identifying weak points within structural components and providing valuable insights into potential stress distributions. This computational approach to model design and testing is more cost-effective and efficient than building and physically testing each individual model. The use of EN 1993-1-2, which provides an elevated temperature stress-strain relationship for stainless steel, is critical in this research project. Furthermore, the data obtained from the experimental programme outlined in EN 1993-1-2 (Li *et al.*, 2021) is critical in providing important information about the reduced strength and stiffness values of steel at elevated temperatures. An elastic-plastic model with the von Mises yield criterion and isotropic hardening is implemented within the ABAQUS numerical framework to accurately capture material behaviour. The input stress-strain curves are derived from the constructed engineering stress-strain relationships (Pournaghshband *et al.*, 2019). and are characterised by multi-linear actual stress and logarithmic plastic strain responses, improving the fidelity and accuracy of the numerical simulations. The research project's comprehensive approach aims to comprehensively understand the behaviour of stainless-steel materials under elevated temperature conditions, effectively identifying critical failure points and potential vulnerabilities. The use of FEA in conjunction with empirical data from experimental testing ensures a robust and reliable evaluation of the material's thermomechanical response, yielding valuable insights for structural design and improving the overall safety and performance of stainless-steel structures exposed to high-temperature environments.

The investigation into the structural behaviour of the Stainless-Steel Beam (SSB) under fire exposure makes use of Finite Element Modelling (FEM) via the ABAQUS software, which serves as a critical validation tool for comparing numerical results with experimental data. To gain a comprehensive understanding of the SSB's response to fire and to investigate the influence of critical parameters governing its behaviour, a comprehensive Finite Element Analysis (FEA) model is developed. The experimental findings inform the use of varying model dimensions, ensuring the numerical representation's fidelity to real-world scenarios. To achieve the best balance of computational efficiency and result accuracy, meticulous mesh convergence research is carried out to determine the optimal mesh density. A seed mesh with approximate global dimensions of 0.25 is used wisely, with the meshing elements seamlessly integrated into the heat transfer manager. The model's boundary conditions precisely mirror those encountered in the experiments, preserving the integrity of the physical test setup, and include pinned supported boundary conditions. To accomplish this, the degrees of freedom for displacement and rotation must be appropriately constrained.

The finite element analysis is performed in two stages: first, the mechanical load is applied, and then the model is subjected to elevated temperatures based on data from the testing programme, accurately simulating the fire exposure scenario. The study hopes to gain valuable insights into the SSB's behaviour under fire conditions by employing this rigorous numerical approach, which will be bolstered by the validation of computational results against experimental data. With its robustness and efficiency, the FEM methodology is a valuable tool for understanding the structural response of stainless-steel beams in high-temperature environments, ultimately improving fire resistance and safety in practical engineering applications.

C. Heat Transfer Analysis

In situations involving a fire, the temperature is not constant but rather increases over time. In light of this, the heat transfer analysis in this study adheres to the ISO834 Standard Fire Curve (BS EN 1991-1-2), a well-established representation of time-temperature relationships during fire incidents. Using the corresponding values from the standard fire curve, this method enables the precise determination of temperature at any given moment throughout the duration of a fire. The numerical model includes a comprehensive heat transfer mechanism that captures the dynamic interaction between the Stainless-Steel Beam (SSB) surface and the surrounding fire. Specifically, the side flange of the SSB is considered the fire-exposed surface, as depicted in Figure 5.

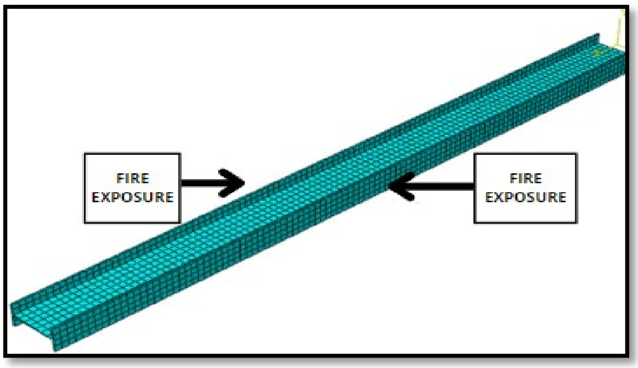

Figure 5. Surface of SSB that is exposed to fire.

To accurately simulate the time-varying temperature fluctuations, the model's amplitude data is derived from the ISO834 Standard Fire Curve (BS EN 1991-1-2) using a tabular format to replicate the changing temperature conditions encountered by the SSB during the fire exposure. By incorporating the ISO834 Standard Fire Curve into the heat transfer analysis, this study intends to investigate the SSB's response under realistic fire conditions, thereby facilitating a thorough comprehension of its thermal behaviour and fire resistance capabilities. Such insights are crucial for improving the fire resistance and structural design of stainless-steel beams in engineering applications.

D. Validation Development on SSB

The development of the steel I-section beam required the use of solid and homogeneous steel, which ensured a consistent and uniform material composition throughout the cross sections of the beam. Subsequently, the section managers were provided with the properties specified in the paper. Notably, the geometric configuration and loading conditions of the beam are symmetrical about the midspan, resulting in a balanced structural response. This symmetrical arrangement is achieved by pinning the end sections' boundary conditions, which promotes stability and equitable load distribution along the beam. For the finite element analysis, precise constraints are imposed on the vertical and lateral displacements of all nodes along the longitudinal axis, eliminating any potential movement and setting these displacements to zero. In contrast, the axial displacement parametric analysis involves applying a load to the beam's mid-top surface. In order to investigate the fire resistance of the beam, the heat transfer analysis model is integrated seamlessly with the structural analysis model. This integration ensures that the fire resistance analysis and heat transfer analysis are consistent with one another, establishing a robust and comprehensive representation of the beam's behaviour under elevated temperature conditions. In an effort to validate the model, a variety of SSB dimensions at high temperatures are generated, allowing for a comprehensive examination of its predictive capabilities. The exported data from ABAQUS are then meticulously compared with experimental data as part of a rigorous validation procedure to confirm the accuracy and dependability of the numerical model within the ABAQUS software framework. The validation process is crucial for establishing confidence in the model's ability to capture accurately the complex response of the SSB under fire conditions.

E. Parametric Investigation on SSB

In the context of fire situations, it is crucial to appreciate the dynamic character of temperature, which fluctuates over time rather than being constant. Consequently, it becomes essential to undertake parametric analyses to completely evaluate the structure behaviour under diverse fire circumstances. These studies require submitting the structure to a series of tests, which may be accomplished quickly through the creation and use of computer models. For this study's third goal, a two-model technique was utilised. The first model simulates the complex heat transport process, capturing the spatiotemporal temperature distribution across the structure. This model accurately replicates the structure's thermal reaction to fire exposure. The results derived from the heat transfer model are then merged smoothly into the second model, which simulates the structural reaction under the impact of external stresses. By combining thermal effects with structural reaction, this method enables a thorough study of the structure's behaviour during fire exposure, taking into account both thermal and mechanical factors. Using this two-model approach, the study attempts to get a greater understanding of the complex relationship between temperature changes and structural performance, so offering a more nuanced evaluation of the fire resistance and load-bearing capability of the structure. This methodological rigour improves our understanding of structure behaviour under a variety of fire situations and has important implications for maximising fire safety and design techniques in engineering applications.

III. RESULT AND DISCUSSION

A. Validation of Finite Element Modelling (FEM) Method with the Experimental Work Results

Validation is a vital step for ensuring the correctness and dependability of the finite element model since it compares the model's predictions against experimental data. In this investigation, the experimental data, as illustrated in Figure 1, were in good agreement with the results of the finite element modelling. The comparison revealed that the two sets of findings were quite consistent. Figure 6 and 7 demonstrates that there were substantial differences between the finite element models and experimental test findings. These disparities indicate that the model may require more refining and modification to more accurately represent the complex behaviour of the structural stainless-steel beam (SSB) at increasing temperatures. The observed variations may be attributable to a variety of variables, such as the intrinsic complexity of material behaviour, the unpredictability of material characteristics, or the simplifications applied to the finite element model. In order to improve the model's prediction capabilities and provide a more realistic portrayal of the SSB's response to fire exposure, it is essential to address these differences. Figure 8 depicts the location of the predicted temperature measurement along the steel beam model. The positioning node is set in the surface's outer flange at the midpoint of the stainless-steel beam. Meanwhile, the vertical and longitudinal positions from the experiments were used to validate the finite element model in the parametric result of the fire loading.

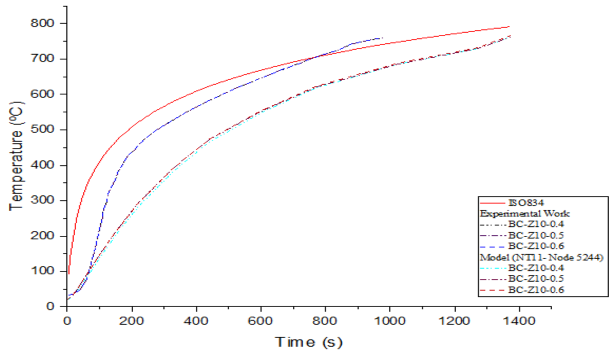

Figure 6. Temperature vs time comparison between FEM modelling and experimental result of under e_o10 mm

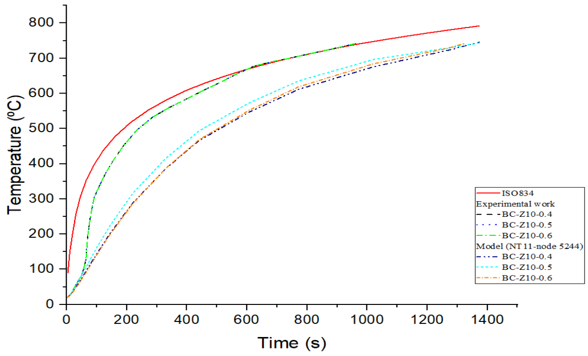

Figure 7. Temperature vs time comparison between FEM modelling and experimental result of under e_o30 mm

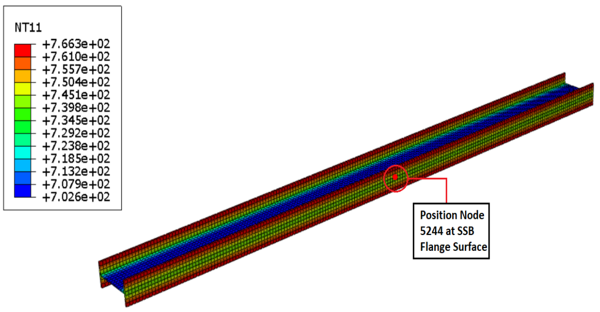

Figure 8. The location of node used during heat transfer analysis were conducted in ABAQUS CAE software

In general, finite element (FE) models are anticipated to initially lean toward a more rigid response. In comparison to Eurocode criteria, however, significant challenges may develop in ensuring the strength of the material at increased temperatures. Nonetheless, it was determined that the results produced from the finite element model were near enough to validate its correctness for the purposes of this investigation. In both the finite element approach and experimental investigation, it is important to note that changes in material behaviour can be impacted by a number of factors. Specifically, the model's description of boundary conditions may not capture the complete side surface of the structural stainless-steel beam (SSB), resulting in the possibility of thermal interaction inconsistencies. In addition, the model may not account for the entire number of thermal interactions between the temperature and the surface of the SSB. In addition, the interactions between the model's constituent pieces and their equivalents in the experimental setup may not be properly coordinated.

In addition, it is essential to recognise the potential constraints of the experimental work, as demonstrated by the proportion of validation findings that differ between the finite element and experimental outcomes, as shown in Tables 6 and 7. The results of the comparison between the modelled and experimental work at node 5244 are presented in Figure 3. The positioning node is set in the surface's outer flange at the midpoint of the stainless-steel beam. Meanwhile, the vertical and longitudinal positions from the experiments were used to validate the finite element model in the parametric result of the fire loading. These percentage differences indicate that the finite element model is generally consistent with the test findings. However, tiny differences in material characteristics between the two methods may account for the observed discrepancies, with the experimental development potentially producing more accurate material property data. Nonetheless, the thermal behaviour of the SSB displays significant agreement between experimental and finite element techniques. In terms of temperature-to-time correlations, the data reveals that both techniques closely comply to the temperature-time curves established by the ISO 834 standard fire curve. In conclusion, the finite element modelling seems to be a helpful and promising method for forecasting the thermal behaviour and reaction of the structural stainless-steel beam at increased temperature settings, despite some disparities between the finite element and actual results. The findings highlight the significance of thorough calibration and validation of numerical models for accurate fire resistance analysis predictions.

Table 1. Validation result of the FEM modelling with experimental result of under $e_0$10 mm

Model	BC-Z10-0.4	BC-Z10-0.5	BC-Z10-0.6
Experimental (⁰C)	760.43	760.43	760.43
FEM Model (⁰C)	761.97	761.78	766.25
Percentage Different (%)	1.97	1.78	6.32

Table 2. Validation result of the FEM modelling with experimental result of under $e_0$30 mm

Model	BC-Z10-0.4	BC-Z10-0.5	BC-Z10-0.6
Experimental (⁰C)	741.66	741.66	741.68
FEM Model (⁰C)	745.56	743.09	742.69
Percentage Different (%)	3.9	1.43	1.01

B. Heat Transfer Analysis Results

For each of the six tested models, the temperature response of the structural stainless-steel beam (SSB) was uniformly distributed during the required exposure length, as demonstrated by the research results. In addition, nodal temperatures (NT11) were rigorously monitored at various points throughout each model's varying size dimensions. The exhaustive data analysis verifies that the finite element model closely resembles the temperature-time curve specified by the ISO 834 standard fire curve, creating a robust alignment with the anticipated temperature-to-correlations. In order to replicate fire exposure, the model underwent a 1372-second heating procedure using the ISO834 Standard Fire Curve (BS EN1991-1-2). The finite element validation approach included a thorough examination of the SSB's outer surface temperature. The boundary conditions examined for the exposed surface comprised a film state of 25 W/m^2K, whereas the film condition value for the unexposed surfaces was 9 W/m^2K. In addition, the radiation interaction on the outer surface of the SSB was accurately modelled to simulate cavity radiation for closed cavities, with an emissivity value of 0.85 W/m^2K.

The SSB temperature profile revealed a quick increase from 0 to 95.72 seconds, followed by a rather consistent increase until the end of the exposure duration of 1372 seconds. Due to the external heat transmission, the outer surface of the SSB suffers higher temperatures than its inside, as seen by this thermal behaviour, which is in perfect accordance with the projected temperature increase as per the ISO 834 Standard Fire Curve. These thermal reactions and temperature distributions seen in SSB models give essential information into the behaviour of the structure during fire circumstances. Understanding the performance and sensitivity of stainless-steel beams when exposed to extreme temperatures is of the utmost importance for guaranteeing maximum fire safety and structural integrity in practical applications. Figure 9 shows the stainless-steel beam's temperature distribution of the BCZ10-0.4 model.

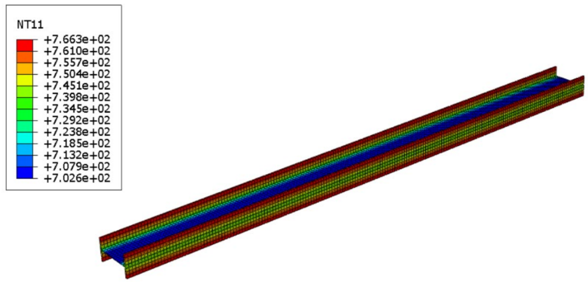

Figure 9. The temperature behaviour of the stainless-steel Beam model

The model was heated for 1372 seconds using the ISO834 Standard Fire Curve (BS EN1991-1-2), and the temperature along the SSBs on the exterior surface was measured using FE validation. The film condition of a fire-exposed surface is 25 W/m2 K. The film condition value for unexposed surfaces is 9 W/m2. The outer surface radiation interaction of SSB on the sheet resembles cavity radiation for closed cavities in the model, which has an emissivity value of 0.85 W/m2 K. The surface temperature of the SSB rises substantially from 0 to 95.72 seconds and then continues to rise horizontally until 1372 seconds. According to the ISO834 Standard Fire Curve, temperature increases in the SSB in the same way that fire does. As a result of the heat transmission from the outside into the SSB, the outer surface will be hotter than the internal component.

C. Stress Strain Behaviours of SSB

The results reported in this part provide vital insight into the stress-strain behaviour of the structural stainless-steel beam (SSB) when exposed to increased temperatures and axial displacement. In particular, the BCZ10-0.6 model was subjected to a complete parametric evaluation that investigated stress-strain fluctuations following exposure to fire as illustrated in Figure 10. This study's stress-strain curve for the SSB revealed maximum stresses and strains of 8.923 MPa and 0.226 m, respectively as depicted in Figure 11. In engineering, stress-strain graphs are used to determine the critical stress level at which a material may fail. Notably, after firing the SSB, the final stress and strain levels decreased by almost 10 percent each. This large drop highlights the major influence of fire exposure on the SSB's ultimate strength. In addition, the examination of the standard temperature curve, ISO 834, demonstrated that the SSB's ability to sustain its initial strength after exposure to fire declines. These findings emphasise the utmost significance of knowing the material behaviour of stainless-steel buildings under fire conditions, allowing engineers to make educated decisions to improve fire safety and structural resilience in actual applications.

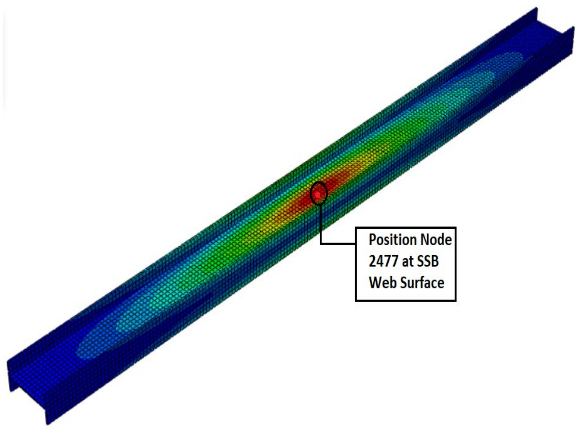

Figure 10. The location of the node used to obtain the stress-strain curve of the stainless-steel beam

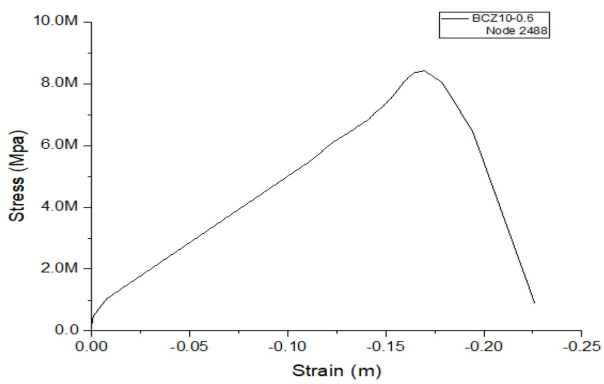

Figure 11. The predicted stress-strain curve of the stainless-steel beam model

D. Axial Load Displacement Behaviour of SSB When Expose to Fire

The structural stainless-steel beam (SSB) was exposed to a maximum load of 80 kN during the parametric analysis utilising finite element techniques. The location of the predicted mid-span deflection was identified as shown in Figure 12. As indicated in Figure 13, no appreciable displacement was seen prior to exposure to the combined effects of load and fire. Nevertheless, when the load was applied, as illustrated in Figure 14, the SSB was able to endure the 80 kN stress for 0.16 seconds. It is possible that careful consideration of loading circumstances throughout the creation of the model affected the observed displacement behaviour. Remarkably, after exposure to fire and under the given stress, the SSB demonstrated the least amount of axial displacement at the web compared to other types. The observable deflections of the beam are determined not only by the externally applied loads and supports but also by the stiffness of the material and the size of the beam. In this context, the significantly lesser displacement of the web may be attributed to its thickness ratio, which is 5.02 mm for the web and 6.93 mm for the flange. This significant variation in thickness ratio shows that the combined impacts of fire exposure and loading had a significant impact on the SSB's displacement behaviour. Such significant insights are crucial for evaluating the structural reaction and performance of stainless-steel beams in real-world fire situations, hence leading to the creation of safer and more durable structural systems.

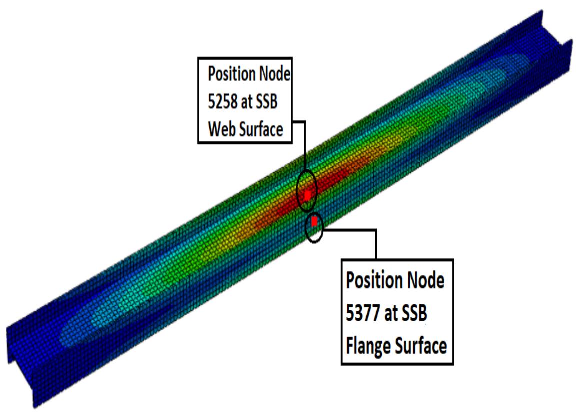

Figure 12. The location of the mid span deflection (node no: 5258) and Flange Surface (node no: 5377) of the stainless-steel beam model

Figure 13. Vertical displacement of SSB before expose to fire and load

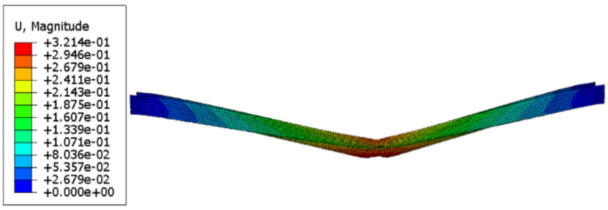

Figure 14. Vertical displacement of SSB after expose to fire and load

Figure 15 depicts a substantial decrease in displacement for the structural stainless-steel beam (SSB) when exposed to fire. In particular, the axial displacement decreases by roughly 7.5% compared to the displacement of the SSB prior to its eventual failure. This discovery emphasises the ability of the SSB to keep its original form and structural integrity under applied stresses and fire conditions. Notably, the magnitude of displacement is a crucial predictor of possible beam failure. In addition, the experimental results reveal that after being exposed to fire, the strength of an SSB built of stainless-steel increases significantly. The initial investigation reveals that the stainless-steel beam is stable even at extreme temperatures. In addition, Figure 10 illustrates the displacement fluctuations of the SSB under various loading circumstances. The results indicate that, compared to the flange portion, the web part of the beam has a 7 percent greater rise in displacement. In particular, the displacement of the web goes from 0 mm to 32 mm, while the displacement of the flange increases from 0 mm to 25 mm. This discrepancy in displacement between the web and flange demonstrates the significant effect of loading and deflection on the SSB, with the web portion exhibiting the most displacement. Overall, these results are crucial for understanding the behaviour and reaction of stainless-steel beams under fire exposure and load circumstances. The substantial increase in strength and the capacity of the beam to retain its shape under unfavourable conditions validate the desirable properties of stainless steel as a structural material, hence enhancing fire resistance and safety in building applications.

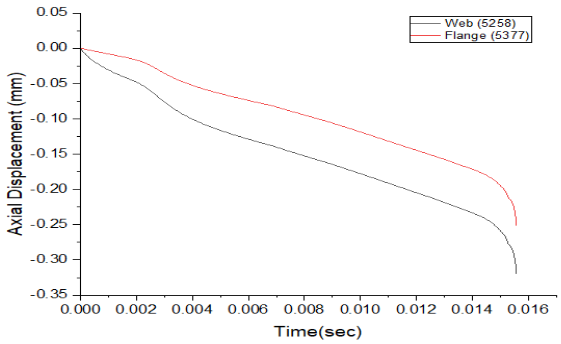

Figure 15. Axial displacement versus time of the SSB

E. Temperature Displacement Behaviour of SSB when Expose to Fire

This section summarises the findings of a thorough examination of the temperature displacement behaviour of a structural stainless-steel beam (SSB) when exposed to extreme temperature circumstances. Following fire exposure, the BCZ10-0.6 model was submitted to a thorough parametric analysis to determine the changes in temperature-induced displacement. As depicted in Figure 16, the SSB temperature displacement curve reveals notable discoveries, with maximum displacements of 0.3201 m and 0.2434 m reported at the web and flange, respectively, when the temperature reached 766.25°C. These important findings provide useful insights into the reaction of the SSB to increased temperatures and its thermal behaviour, offering information on how the structure experiences displacement under fire-induced thermal stress. Understanding temperature displacement characteristics is essential for developing fire resistant constructions and preserving the structural integrity of stainless-steel beams in high-temperature settings. These findings contribute to the progress of structural engineering knowledge and give crucial data for fire-resistant design considerations in a variety of building applications.

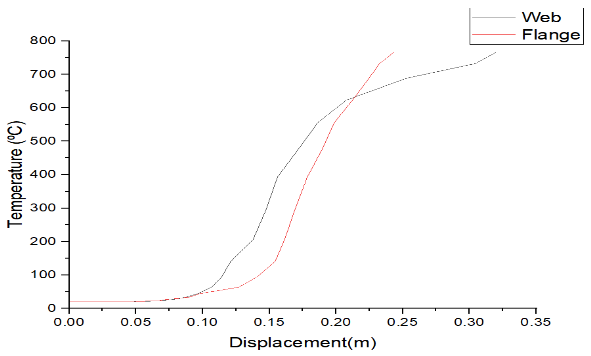

Figure 16. Temperature versus Displacement of the SSB

IV. CONCLUSION

This study concludes that finite element analysis (FEA) is useful in forecasting the thermal behaviour and reaction of stainless-steel beams (SSBs) when exposed to extreme temperatures. The numerical analysis and experimental data supported the validity and reliability of the suggested FEA method for analysing the performance of SSBs exposed to fire. The consistency between numerical simulations and actual investigations demonstrates that the finite element model well captures the thermal behaviour of SSBs. However, it is notable that a little mean average discrepancy of 2.74 percent was discovered between the numerical and experimental data for the various models' ultimate temperature values. This difference is likely attributable to modest changes in material qualities and boundary circumstances. The findings demonstrate the potential of SSBs as excellent fire-resistant reinforcing components for beam constructions. Comparing the FEA findings with experimental data reveals excellent structural behaviour, especially in terms of enhanced strength at increasing temperatures. Notably, the SSBs demonstrated less displacement under high load in the flange area than in the web section, indicating their resistance to temperature extremes. The current work contributes to the progress of fire-resistant design strategies in structural engineering by providing significant insights into the behaviour of SSBs in fire situations. Consideration of more robust SSBs may enhance the overall performance and safety of fire-exposed buildings. It is essential to recognise that the results of this investigation lay the groundwork for more extensive studies in the field and that future research could explore additional parameters and further refine the modelling techniques to more accurately capture the intricate complexities of SSBs' behaviour under different fire scenarios.

V. ACKNOWLEDGEMENT

The authors would like to thank Universiti Teknologi MARA for providing financial assistance through the Geran Penyelidikan MyRA (600-RMC/GPM LPHD 5/3 (063/2021)). The authors would also like to thank the Civil Engineering Studies, College of Engineering, Universiti Teknologi MARA, Cawangan Pulau Pinang, Permatang Pauh Campus, Permatang Pauh, Pulau Pinang, and also the School of Civil Engineering, College of Engineering, Universiti Teknologi MARA, Shah Alam, Selangor for the contribution and assistance to the advancement of the research.

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